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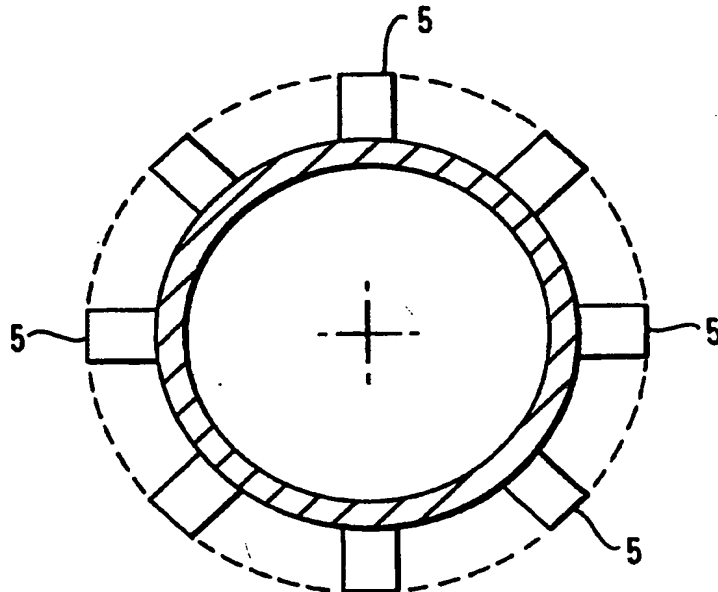
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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶: G01N 29/22, G10K 11/00	A1	(11) International Publication Number: WO 96/12951 (43) International Publication Date: 2 May 1996 (02.05.96)
(21) International Application Number: PCT/GB95/02482 (22) International Filing Date: 20 October 1995 (20.10.95) (30) Priority Data: 9421187.7 20 October 1994 (20.10.94) GB 9517794.5 31 August 1995 (31.08.95) GB (71) Applicant (for all designated States except US): IMPE- RIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE [GB/GB]; Exhibition Road, South Kensington SW7 2BX (GB). (72) Inventors; and (75) Inventors/Applicants (for US only): CAWLEY, Peter [GB/GB]; 84 Shakespear Road, London W3 6SN (GB). ALLEYNE, David, Nathaniel [GB/GB]; 565 Rayners Lane, Harrow HA5 5HP (GB). CHAN, Che, Wan [-/GB]; 18 Ethelbert Road, St. Pauls Cray, Orpington, Kent BR5 3JW (GB). (74) Agent: SHINDLER, Nigel; Batchellor, Kirk & Co., 2 Pear Tree Court, Farringdon Road, London EC1R 0DS (GB).		(81) Designated States: GB, JP, US, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published <i>With international search report.</i> <i>Before the expiration of the time limit for amending the</i> <i>claims and to be republished in the event of the receipt of</i> <i>amendments.</i>

(54) Title: INSPECTION OF PIPES**(57) Abstract**

An apparatus and a method for inspecting elongate members, especially pipes using Lamb waves. The apparatus and method provide for the propagation of an axi-symmetric Lamb wave of a single mode in one direction along the pipe. A means is provided to receive the Lamb wave after its passage along the pipe and convert the received wave for storage, processing and analysis to determine whether or not there are faults present in the pipe. The apparatus includes at least one and usually several excitation rings each comprising a plurality of Lamb wave exciters (5) deployed in equiangular spacing in a ring clamping means whereby each exciter can be pressed with equal force against the surface of the pipe under inspection.



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INSPECTION OF PIPES

The present invention is concerned with the inspection of elongate members generally, but especially pipes, rods, beams, struts and other structural members in order to ascertain their condition, especially whether or not they are subject to fatigue, corrosion or erosion. The invention will be particularly described with reference to its industrial application for inspecting pipes but this is not to be construed as a limit of its application.

The inspection of pipe condition for such deleterious effects as corrosion, erosion or fatigue is frequently complicated by the need to shut down plant, the provision of obscuring lagging and the difficulty in imaging the interior of the pipe. Existing techniques for the inspection of pipes include removing any lagging to inspect the pipe visually, and then employing ultrasonic inspectoscopes or the like to look for defects developing on the inside of the pipe. An alternative technique involves mounting an ultrasonic or eddy current probe on a sledge which is then towed along the inside of the pipe. As with the aforementioned external approach every point along the pipe length must be scanned by the probe resulting in very long inspection times.

It is an object of the present invention to provide an apparatus for inspecting the condition of a pipe which alleviates the aforementioned disadvantages of the prior art.

According to one aspect of the present invention there is provided apparatus for inspecting a pipe comprising at least one ring of angularly spaced wave exciters adapted to propagate one of:

- (a) a single mode axially symmetric Lamb wave,
- (b) a single torsional mode wave,
- (c) a single flexural mode wave,

in a single direction along a pipe,

receiving means capable of receiving the waves
and,

analysing means capable of analysing the received wave to assess the condition of the pipe.

Preferably the wave will be an axisymmetric Lamb wave.

The excitation assembly is preferably composed of a first excitation ring which can be secured to the exterior of the pipe wall and controlled to propagate axi-symmetric Lamb waves along the pipe.

The first excitation ring propagates many modes of axi-symmetric Lamb waves in both the forward and reverse directions along the pipe. The signals received by the receiving means using such a simple excitation assembly are extremely difficult to analyse usefully. Accordingly the assembly may advantageously include second and third excitation rings, each of a construction similar to the first excitation ring. The first, second and third excitation rings cooperate to suppress all but a single axi-

symmetric mode propagating in a single "forward" direction. If only a single extra excitation ring is included in the excitation assembly the reverse direction propagating waves or the unwanted modes can be suppressed by cooperation of the excitation rings in the assembly. Thus the pipe can be inspected by means of a single axi-symmetric mode Lamb wave propagating in one direction thereby greatly simplifying the analysis of the waveform received by the receiving means.

The axi-symmetric unidirectionally propagating Lamb wave can be received by a receiving means of similar construction to the excitation assembly at a position longitudinally remote from the excitation assembly. However a more convenient and economic receiving means can be provided by wave exciter/transducers of the excitation assembly. In this preferred latter case the waveform received will be a reflection from a structure in the pipe wall. The reflected wave will have been altered by any structure in the pipe wall; such structures may include cracks or deformations which can thus be detected by analysis of the received waveform.

It will be appreciated that under some circumstances the apparatus according to the invention may be used as a permanent installation for frequent or continuous inspection of the pipe condition. However, the apparatus can be adapted to be readily mounted and dismounted for intermittent pipe inspection.

The preferred operating frequency of the Lamb wave

will depend upon the size of the pipe but will ordinarily be in the range 10kHz to 500kHz. Preferably the fastest propagating mode of Lamb wave will be selected for the inspection.

The excitation of Lamb waves has previously been achieved by the use of exciters comprising electromagnetic acoustic transducers (EMAT's) but EMAT's are too large to be used in the construction of an excitation assembly capable of inducing axi-symmetric Lamb waves in a pipe which will commonly be between 70mm and 460mm.

Accordingly a further aspect of the present invention is a wave exciter/transducer characterised in that a piezoelectric element is polarised to deform when a voltage is applied across its faces and has a backing structure engageable by means to clamp the piezoelectric element to the pipe whereby a wave can be propagated in the pipe in response to a control signal and to generate a wave signal in accordance with a wave traveling through the pipe.

In a first possible embodiment of the exciter the piezoelectric element is an expansion type element which expands and contracts longitudinally and the backing structure is provided by a casing filled with a lossy material. The casing and lossy material serves the purposes of protecting electrical connections to the element, providing flexural stiffness to protect the very brittle element when it is pressed onto a rough pipe surface and damping our reverberations so that the Lamb wave exciter

outputs a faithful reproduction of the excitation signal.

Experience with the expansion type transducer described above has shown that even when extreme care is taken in setting up the transducers there was a persistent baseline signal of about 1% of that of the mode of interest and setting up to obtain such a low baseline signal meant that a test could take as much as two hours. This is impractical for industrial use.

The aforementioned problem is alleviated by an alternative and preferred embodiment of the exciter wherein the element may be a shear polarised piezoelectric element. In this embodiment the surface of the element which engages the pipe is displaced in only one direction at a time, the direction changing in accordance with the excitation waveform but always parallel to the opposite surface of the element by which it is mounted to the block. The force on the pipe is therefore instantaneously applied in one direction irrespective of the position of contact on the pipe and varying in magnitude and direction in accordance with the waveform applied to the element.

Experience with transducers housed in a casing filled with the lossy material shows that, at the operating frequency of approximately 70 kHz the damping is not adequate and when the transducer is used as a receiver a reverberation tail appears in the response. The extent of this tail varies between different transducers of nominally the same design, making it very difficult to obtain an

axially symmetric excitation ring. The cause of the reverberation tail is a resonance of the exciter which frequently occurs between 70 and 80 kHz but may occur at other operating frequencies. The operating frequency of the exciter is about 70 kHz and so causes a major problem.

To alleviate the aforementioned problem the piezoelectric element is backed with a rigid backing which moves all resonance of the transducer beyond the operating frequency range. The rigid backing is preferably a steel backing block and may be applied to either the expansion or shear polarised type of piezoelectric element. A further advantage of this type of backing structure is a reduction in the size of each Lamb wave exciter and it is very robust.

Each excitation ring may be comprised of a plurality of the exciters equally spaced from each adjacent exciter and clamped against a wall of the pipe by the clamping means. Each exciter can act as a wave receiver by converting the mechanical force of the wave passing through the pipe to an electrical signal. Thus the exciter will in some cases be a transducer.

It may be possible to employ an excitation ring comprising a plurality of wave exciter/transducers equiangularly spaced around the pipe under inspection where each exciter is in communication with a corresponding channel of the analysing means so that non-axisymmetric modes of the waves can be received for analysis.

A receiver assembly may be controlled to receive

only a single mode of the propagating wave traveling in a single direction.

Embodiments of apparatus for inspecting a pipe using Lamb waves and constructed according to the invention will now be described, by way of example only, with reference to the accompanying figures; in which,

Figure 1 shows the group velocity dispersion curves for a pipe having a diameter of 76.2mm (3 inch) and a wall thickness of 5.5mm for both axi-symmetric $L(*,*)$ and non axi-symmetric $F(*,*)$ Lamb wave modes propagated along the pipe,

Figure 2 diagrammatically illustrates a Lamb wave excitation assembly clamped to a pipe,

Figure 3 is a block diagram of the apparatus,

Figure 4 is a sectioned elevation of a first embodiment of a single Lamb wave exciter,

Figure 5 is a sectioned end elevation of the Lamb wave exciter in figure 4,

Figure 6 is a diagrammatic sectional view through the pipe showing the symmetric deployment of some of the Lamb wave exciters in one Lamb wave exciter ring.

Figure 7 shows a clamping means by which the excitation assembly can be secured to the pipe,

Figure 8 depicts an expansion transducer deployed using asymmetric load clamping means,

Figure 9 illustrates the deformation of a shear polarised piezoelectric transducer,

Figure 10a portrays the signal received where a piezo electric shear transducer is used,

Figure 10b shows the signal received where an expansion transducer is used, and

Figure 11 depicts a second embodiment of a Lamb wave exciter.

Figure 1 shows that at a desired operating frequency of 70 kHz the fastest propagation mode in a 76.2mm diameter pipe with a wall thickness of 5.5mm is the $L(0,2)$ mode as opposed to the $L(0,1)$ mode and it is this Lamb wave mode which is used to inspect the pipe. The $L(0,1)$ and $L(0,2)$ wave modes are differently propagating axi-symmetric wave modes. The difference between them is in the distribution of displacements and stresses through the pipe. The terminology is more fully explained in the article by M.G. Silk and K.F. Bainton in the journal "Ultrasonics" of January 1979 at pp 11-19 and entitled The propagation in metal tubing of ultrasonic wave modes equivalent to Lamb waves.

Figure 2 shows a length of the pipe 1 to which a Lamb wave excitation assembly 2 of the apparatus is clamped. The excitation assembly 2 comprises a first excitation ring 3A (which is shown in more detail in figure 6) a second excitation ring 3B, and a third excitation ring 3C. Each ring is of similar construction to the ring 3A shown in figure 6.

The excitation rings 3A, 3B, 3C are each comprised

of a set or belt of symmetrically deployed Lamb wave exciter/transducers 5, typically 16 for a 3 inch diameter pipe and 32 for a 6 inch diameter pipe. The minimum number of Lamb wave exciters required in a ring is related to the highest order non-axisymmetric mode in the dispersion diagram at the highest frequency present in the excitation signal. If this mode order is say 13 then the minimum number of elements is 14. Each Lamb wave exciter comprises a high impedance piezoelectric element 6 and is illustrated in detail in figures 4 and 5 or 11. In use each of the Lamb wave exciters is pressed into operative engagement with the surface of the pipe 1 by a clamping means which for this example of the apparatus applies a load of 40 N to every one of the exciters. This arrangement provides sufficient coupling between the pipe 1 and the exciters 5 to make a coupling fluid unnecessary.

An example of a suitable clamping means is shown in figure 7. This clamping means consists of a ring 19 having an internal aperture 20. Spacer means such as three radially extending screws (not shown) are located at 120° intervals around the ring 19. The screws are adjustable to engage the pipe wall and support the ring coaxially around the pipe so that it is spaced from the pipe. This minimises contact with the pipe, and hence minimises any damping of the desired waves and also reduces any wave reflection caused by the clamping means. A plurality of radially extending through holes 21 are equiangularly spaced around the ring 19.

Sufficient through holes 21 are provided to enable the required number of Lamb wave exciters 5 to be mounted one in each through hole 21. Each Lamb wave exciter 5 is mounted on the end of an elongate push rod 22. The push rod 22 is slidably received into an externally threaded sleeve 23 so that a compression coil spring 24 acting between the sleeve 23 and an abutment 25 on the rod 22 tends to project the rod 22 longitudinally. The Lamb wave exciter 5 is installed in the clamping means by screwing the sleeve 23 into the internally threaded hole 21 so that the Lamb wave exciter 5 is pressed against the exterior of the wall of the pipe 1 by the action of the spring 24. The load can be adjusted by screwing and unscrewing the sleeve 23.

In a preferred form of the clamping means, the ring 19 is split radially into one or more separable parts 19a, 19b. In the example illustrated in figure 7 the two parts 19a, 19b, are joined together by two hinge and bolt assemblies generally designated at 26a and 26b. Each hinge and bolt assembly comprises a pair of brackets 27a, 27b. The bracket 27a being mounted on a first part of the ring 19 adjacent where the ring is split, and each bracket 27b being similarly mounted upon the other ring part 19b.

One of the brackets 27a has a through hole 28 in it which extends tangentially to the ring and is of sufficient diameter for an allen key bolt 29 to be received through it. The through hole 28 is not threaded. Each bracket 27b also includes a tangentially extending aperture into which the

bolt 29 is received. The bolt 29 screws into a pivot pin 30 mounted to extend parallel to the axis of the ring 19. The aperture in each bracket 27b allows the bolt 29 to pivot when it is screwed into the pivot pin 30.

The bracket 27a in the assembly 26b differs from the one in the assembly 26a in that the bracket 27a consists of two forks which allow the bolt 29 to be swung out from the bracket when loosened so allowing the ring parts 19a, 19b to be hinged apart around the pivot pin 27b in the other of the brackets.

Although the preferred form of mounting means is the hinged split ring described, it is possible to use a simple ring slipped onto the end of the pipe or a split ring without the hinge and bolt assemblies described but with simple bolt together brackets, overlocking fastenings, buckle and belt type fastenings and a wide range of other mechanisms. The ring shaped mounting means is preferred but any structure which will take up a ring like shape and provide support for the Lamb wave exciters may be suitable, for example, a polygonal structure or an articulated belt structure.

A detailed section through one of the expander type exciter elements is shown in figures 4 and 5. The piezoelectric element 6 is elongate and polarised so that it expands and contracts along its length. Elements of this type are known for use as strain gauges. The element 6 has a backing structure comprising a casing 7, fabricated from

Tufnel, in the base of which it is housed. The casing has upright opposing side walls 8 and end walls 9 and a sealing cover 10. A miniature coaxial cable 11, for connection of the piezoelectric element 6 to control and analysis instrumentation, penetrates the cover 10 and is connected with the piezoelectric element 6 within a chamber 12 formed by the casing. A thin face plate shim 13 is secured against the face of the piezoelectric element 6 to provide a wear plate which protects the piezoelectric element 6 so as to freely transmit forces from the pipe to the piezoelectric element. The shim 13 must be sufficiently thin that its shear stiffness is high enough not to interfere with the coupling of the piezoelectric element 6 with the pipe 1. In the embodiment the shim is of 0.06mm thick steel or brass and may be electrically insulated from the piezoelectric element at the bondline between them. However, the shim 13 may be of a non-conducting material to electrically insulate the piezoelectric element 5. The chamber 12 is filled with tungsten loaded epoxy which is a lossy material serving the purposes of protecting the gauge and electrical connections, providing flexural stiffness so that the very brittle piezoelectric element 6 is not damaged when pressed against a rough pipe surface and it damps out reverberations so that the transducer outputs a faithful reproduction of an excitation signal applied to it or, when used as a receiver, it generates a voltage corresponding to a wave passing it. Thus the lossy material provides means to accommodate pipe

surface roughness and to damp out reverberations.

Figure 9 diagrammatically shows a shear polarised piezo electric transducer 6A which may be used in preference to the expansion type piezo electric transducer 6. With this type of transducer the face engaging the pipe wall moves in one direction only parallel to the pipe axis and so exerts a force in the same direction over its full length. Figures 10a and 10b illustrate the improvement achieved in signal clarity when a shear polarised transducer is used. Figure 10a shows the received signal obtained with a single shear polarised transducer loaded at three different positions along its length. It can be seen that the magnitude of the response is similar at the three positions and, crucially the phase is the same. Figure 10b shows the result of a similar experiment with an expansion type transducer where clear phase changes can be seen. The experiments were with a single transducer instead of a ring so that a significant amplitude of non axially symmetric modes can be seen.

Figure 11 shows a second embodiment of a single Lamb wave exciter for use in an excitation ring. In this embodiment the shear polarised piezoelectric element 6A as described above, is adhesively bonded to a rigid block 31. In this case the rigid block 31 is made of steel and the bonding is achieved by an epoxy cement. A face shim 32, which may be made of brass, is bonded to the face of the piezoelectric element 6A. A passage 33 is formed through the backing block 31 and provides protective support for the

electrical connections to the piezo electric element 6A. The rigid block backing structure can usefully back the expansion type piezoelectric element.

Each Lamb wave exciter ring 3 is controlled via the instrumentation shown in figure 3 so that each of the exciters 6 in any one exciter ring 3 act in phase. The instrumentation comprises a computer, which in this case is a personal computer 14 which computes the necessary excitation signals for each exciter ring 3A, 3B, 3C. The excitation signals are then fed to a multi-channel signal generator 15 which in the embodiment described has three channels to supply signals to each of the excitation rings 3A, 3B, 3C. The signal generator 15 will have sufficient channels to supply as many excitation rings as are desired. More than three rings may be desired in some circumstances, e.g., to amplify the desired single mode Lamb wave. The excitation signals are then fed to an amplifier 16 which amplifies each channel of the excitation signals separately and applies them to the excitation rings 3 so that the excitation assembly generates a signal $L(0,2)$ axi-symmetric mode Lamb wave propagating in one direction down the pipe.

In some applications modes other than the $L(0,2)$ mode may be employed.

Different numbers of exciter rings 3 may be employed in order to suppress undesired axi-symmetric modes and to limit the propagation of the desired mode to one direction. In the currently preferred format, three rings are employed,

successive rings being separated by a distance L as shown in Fig 2. This distance L is set to be:

$$L = \frac{(2m+1)\lambda_1}{2}, \text{ m is integer}$$

where λ_1 is the wavelength of the mode which is to be suppressed in both directions. In the preferred format, $m=0$ so

$$L = \frac{\lambda_1}{2}$$

However, due to the physical size of the rings, it is not always possible to achieve separations small enough to implement this, so m may be set to a larger integer.

The signal applied to the first exciter ring 3A is a toneburst centred on the desired frequency (commonly around 70 kHz) enclosed in a Hanning or Gaussian window to limit the bandwidth. The signal applied to the third ring 3C is identical to that applied to ring 3A but delayed by a time T given by:

$$T = \frac{\pi}{\omega} \left((2n + 1) - \frac{\lambda_1}{\lambda_2} \right), \text{ n is integer}$$

where ω is the centre frequency of the toneburst (expressed in rad/sec) and λ_1 and λ_2 are the wavelengths at the centre frequency of the mode which is to be suppressed in both directions and the desired mode which is to be

suppressed in the backward direction respectively.
Generally, n is set to zero so:

$$T = \frac{\pi}{\omega} \left(1 - \frac{\lambda_1}{\lambda_2} \right)$$

The signal applied to the middle exciter ring 3B is the sum of the signals applied to rings 3A and 3C.

This arrangement suppresses the undesired mode in both directions at the centre frequency of the input toneburst, but not at the other frequencies present in the signal. If the desired mode is non dispersive (ie its velocity does not vary with frequency) then propagation of this mode in the backward direction is suppressed at all frequencies present in the input toneburst. However, if the mode is dispersive then suppression in the backward direction is only achieved at the centre frequency. In this case, it is desirable to modify the signal applied to the third ring 3C.

Suppose that the phase velocity of the desired mode is a function of frequency, $c = g(\omega)$. Then the wavelength, λ is given by

$$\frac{2\pi C}{\omega} = \frac{2\pi g(\omega)}{\omega}$$

Suppose that the excitation signal applied to the first ring is $x(t)$ and the Fourier transform of this signal is $X(\omega)e^{i\omega t}$. At each frequency we want the excitation

signal applied to the second ring to lag that applied to the first ring by T where

$$T = \frac{\pi}{\omega} - \frac{L}{g(\omega)}$$

and L is the spacing between the exciter rings. Then the Fourier components of the required signal are given by

$$Y(\omega) = X(\omega) e^{i\omega T}$$

and the excitation signal applied to the second ring is given by the inverse Fourier transform of $Y(t)$,

$$y(t) = \int Y(\omega) e^{i\omega t} d\omega$$

where the integral is taken over the full bandwidth of the signal.

The signal applied to ring 3B will again be the sum of the signals applied to rings 3A and 3C. A similar procedure may be used in reception to improve the analysis of received signals comprising a dispersive mode.

The cancellation of more than one unwanted axisymmetric mode requires additional excitation rings. Additional excitation rings may also be useful for increasing the amplitude of the desired single axisymmetric mode in the forward direction.

If the only object of using more than one exciter

ring is to suppress backward propagation of the mode we wish to excite in the forward direction then it is advantageous to let $L = \lambda/4$. Then, T is a quarter period at the centre frequency of the excitation signal and it may be shown that the amplitude of the forward propagating wave is maximised at this frequency.

In the embodiment the excitation elements also serve as receivers, thus a Lamb wave that has been propagated down the pipe 1 and reflected back up the pipe 1 disturbs the piezoelectric elements of each Lamb wave exciter in the exciter rings 3. This disturbance causes the piezoelectric elements to generate a voltage signal which is applied to the instrumentation shown on the right in figure 3. Thus each exciter ring 3 generates a corresponding signal. Each of these signals is fed, one each to each one of an array 17 of high bypass filters and then to a receiver amplifier 18 before being supplied to a digital to analogue converter 19 and then to the computer 14 for analysis. The high bypass filters may be set at 10kHz.

The signals received at each ring may be processed in software using an analysis similar to that used to produce the excitation signals for single mode, single direction propagation. The output of this processing is a signal comprising a single, axi-symmetric mode generated by reflections from features in the pipe. It is also possible to employ one receiver channel per Lamb wave exciter/transducer, rather than one per ring. If this is

done it is possible to employ a more sophisticated analysis to determine the amplitudes of other, non-axisymmetric modes present in the reflected signal which may be produced by mode conversion at features in the pipe. One way of carrying out this analysis is described in: Alleyn D. N., and Cawley P., 'A 2-dimensional Fourier transform method for the measurement of propagating multi-mode signals', J Acoust Soc Am, Vol 89, pp1159-1168, 1991. This more sophisticated process can give more information about the nature and size of features in the pipe.

Figure 8 diagrams an expansion type piezoelectric transducer element 6 in which the clamping load is applied to the front edge of the transducer element.

Claims

1. An apparatus for inspecting a pipe comprising at least one ring of angularly spaced wave exciters adapted to propagate one of:

- (a) a single mode axially symmetric Lamb wave,
- (b) a single torsional mode wave,
- (c) a single flexural mode wave,

in a single direction along a pipe,
receiving means capable of receiving the waves
and,

analysing means capable of analysing the received
wave to assess the condition of the pipe.

2. Apparatus according to claim 1 wherein the excitation assembly is composed of a first excitation ring (3A) which can be secured to the exterior of a pipe wall and controlled to propagate the waves along the pipe.

3. Apparatus according to claim 1 or claim 2 wherein the excitation assembly comprises a second excitation ring (3B) and a third excitation ring (3A) which are controlled in co-operation with the first excitation ring to suppress the propagation of unwanted modes of the waves and to suppress the propagation of the waves in the reverse direction along the pipe.

4. Apparatus according to any one of the preceding claims wherein at least one of the excitation rings (3) acts as a receiving means.

5. Apparatus according to any one of the preceding claims wherein each excitation ring (3) comprises a plurality of wave exciters (5) supported in equiangularly spaced relation for engagement with a pipe wall by clamping means.

6. Apparatus according to claim 5 wherein the clamping means comprises a ring (19) with an internal diameter sufficient to be spaced from the pipe wall when clamped thereto, a plurality of spacer means engageable between the ring (19) and the pipe wall to secure the ring in coaxially spaced relation around the pipe wall, and said wave exciters (5) being equiangularly spaced around the ring to be engageable with the pipe wall.

7. Apparatus according to claim 6 wherein, in use, the clamping means applies a uniform force to each wave exciter (5) to press each wave exciter against the pipe wall with the same force.

8. Apparatus according to any one of claims 5 to 7 wherein the ring (19) is radially split to allow it to be located around the pipe.

9. Apparatus according to any one of claims 6 to 8 wherein instrumentation is provided to control the wave exciters (5) in any single ring to act in phase.

10. Apparatus according to any one of the preceding claims wherein a plurality of wave exciter/transducers (6) are equiangularly spaced around the pipe under inspection each said exciter (6) being in communication with a corresponding channel of the analysing means whereby non-axisymmetric modes of the waves can be received for analysis.

11. A wave exciter/transducer characterised in that a piezoelectric element (6) is polarised to deform when a voltage is applied across its faces and has a backing structure engageable by means to clamp the piezoelectric element (6) to the pipe whereby a wave can be propagated in the pipe in response to a control signal and to generate a wave signal in accordance with a wave traveling through the pipe.

12. An exciter according to claim 11 wherein the piezoelectric element (6) is a shear polarised piezoelectric element (6A).

13. An exciter according to claim 11 or 12 wherein

the backing structure is provided by a rigid backing block (31).

14. An exciter according to any one of claims 11 to 13 wherein the pipe engageable face of the piezoelectric element (6) is protected by a face shim (13, 32) secured to it.

15. A method of inspecting a pipe comprising the steps of:

propagating a wave of a single mode in one longitudinal direction along the pipe,

receiving the propagated wave and analysing said wave to determine what structures are present in the pipe.

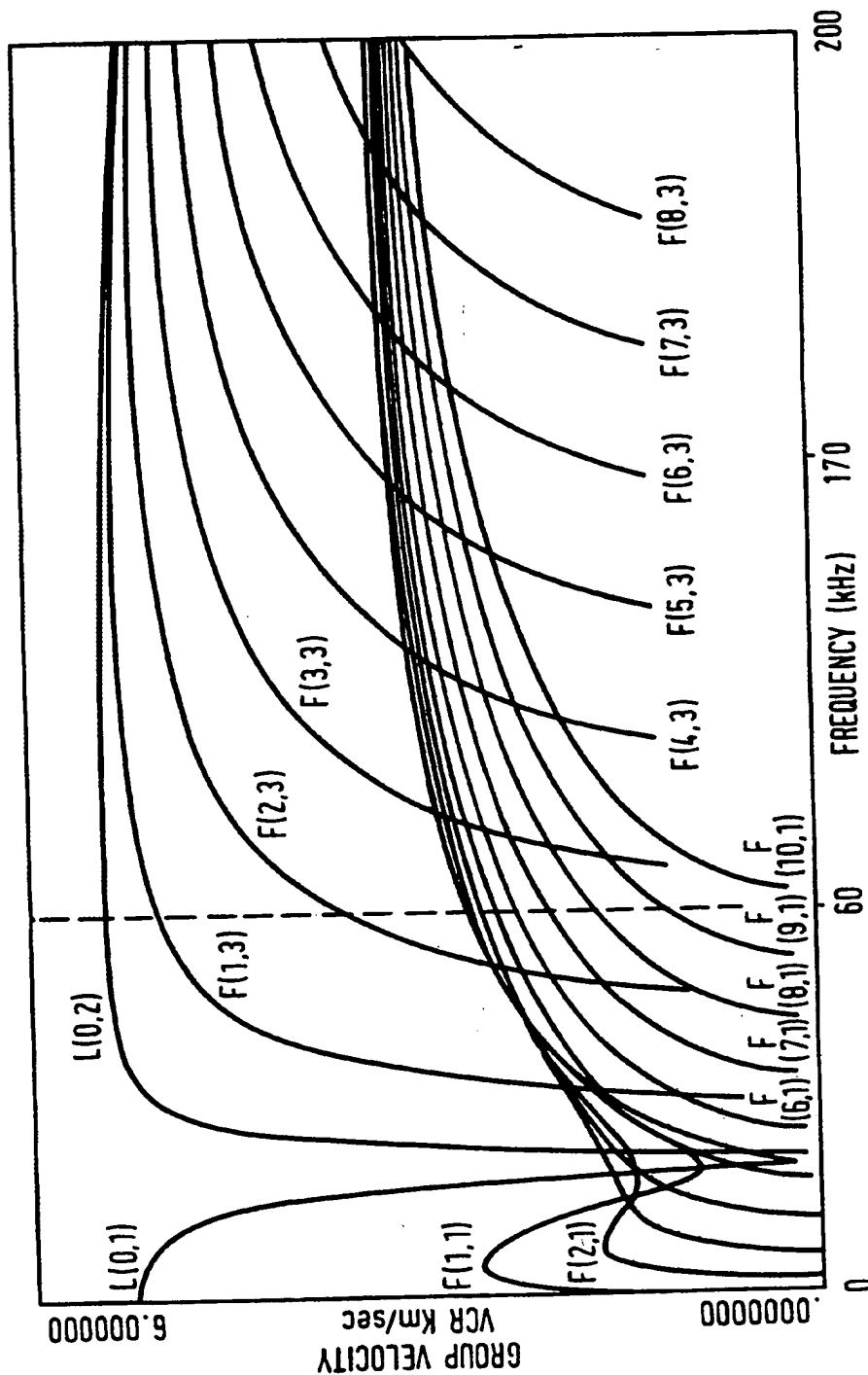
16. A method according to claim 15 comprising the steps of propagating an axi-symmetric Lamb wave in the pipe,

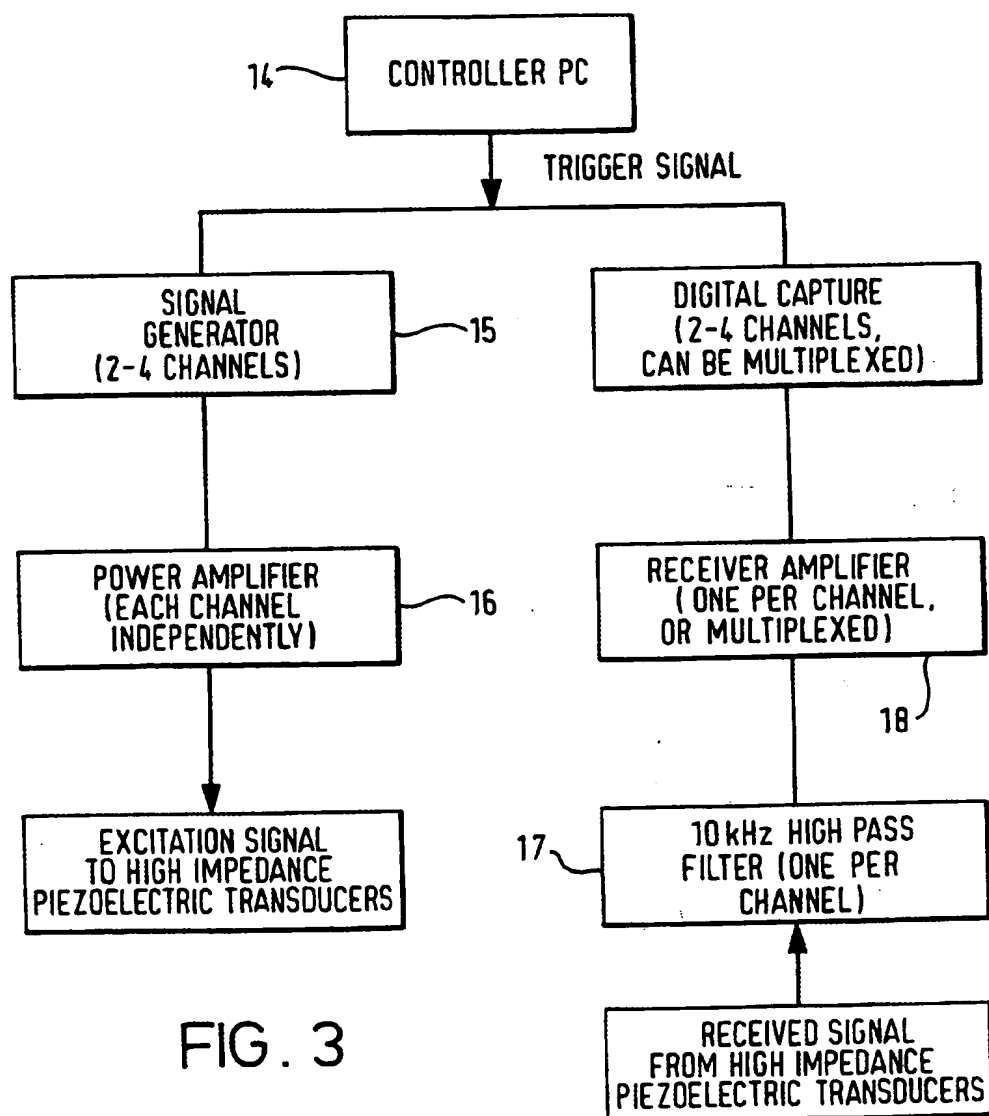
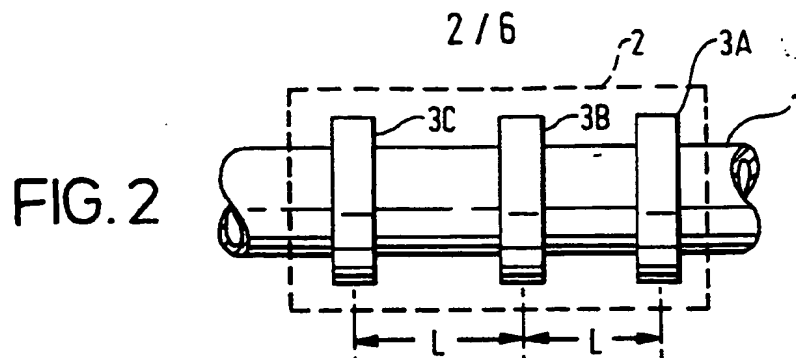
suppressing all but one mode of the Lamb wave propagating in either longitudinal direction along the pipe,

suppressing the propagation of any Lamb wave in one longitudinal direction of the pipe,

in order to propagate an axi-symmetric Lamb wave of a single mode in one longitudinal direction along the pipe.

FIG. 1





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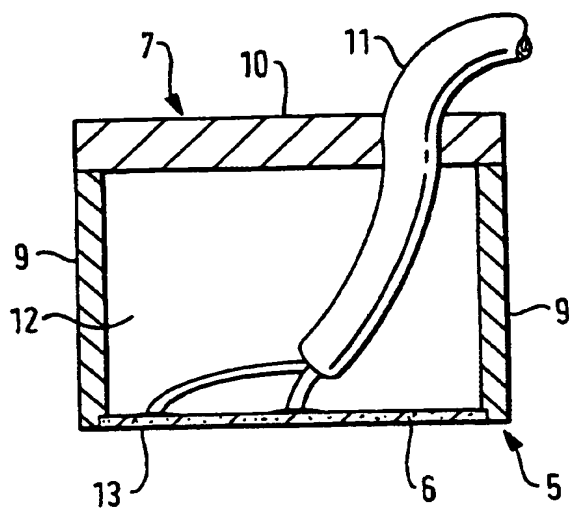


FIG. 4

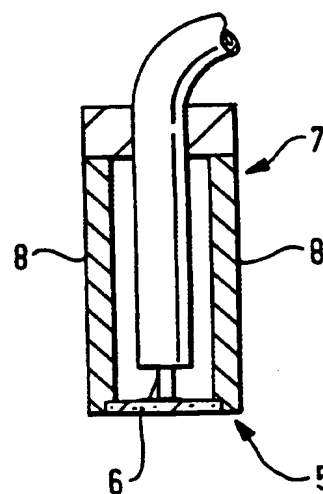


FIG. 5

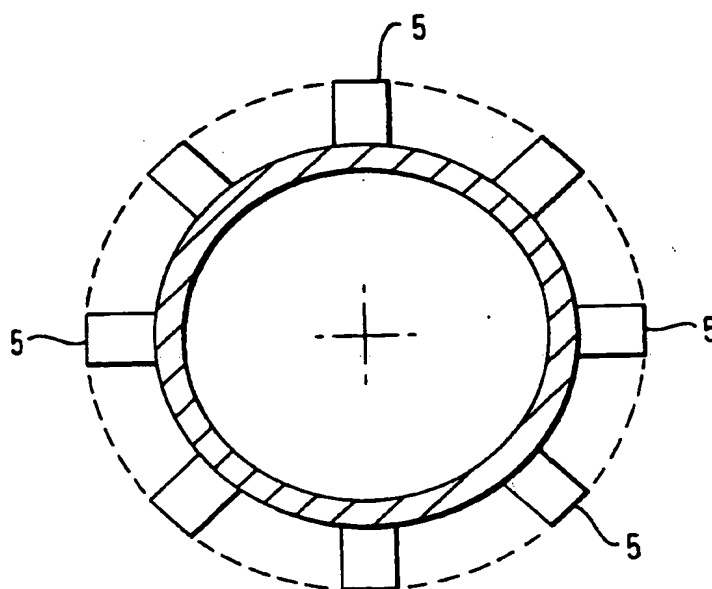


FIG. 6

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FIG. 7

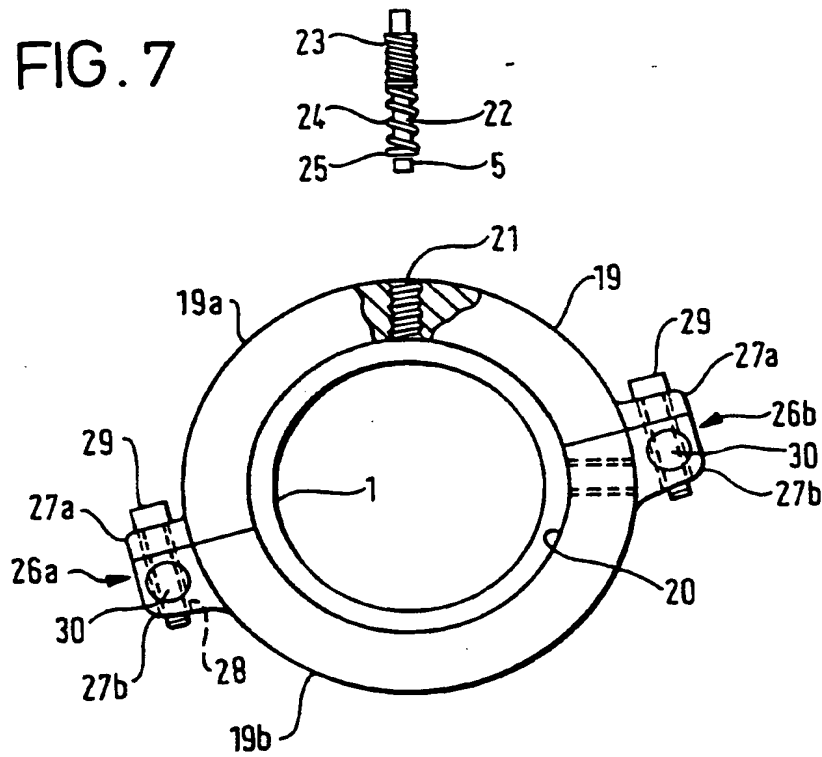
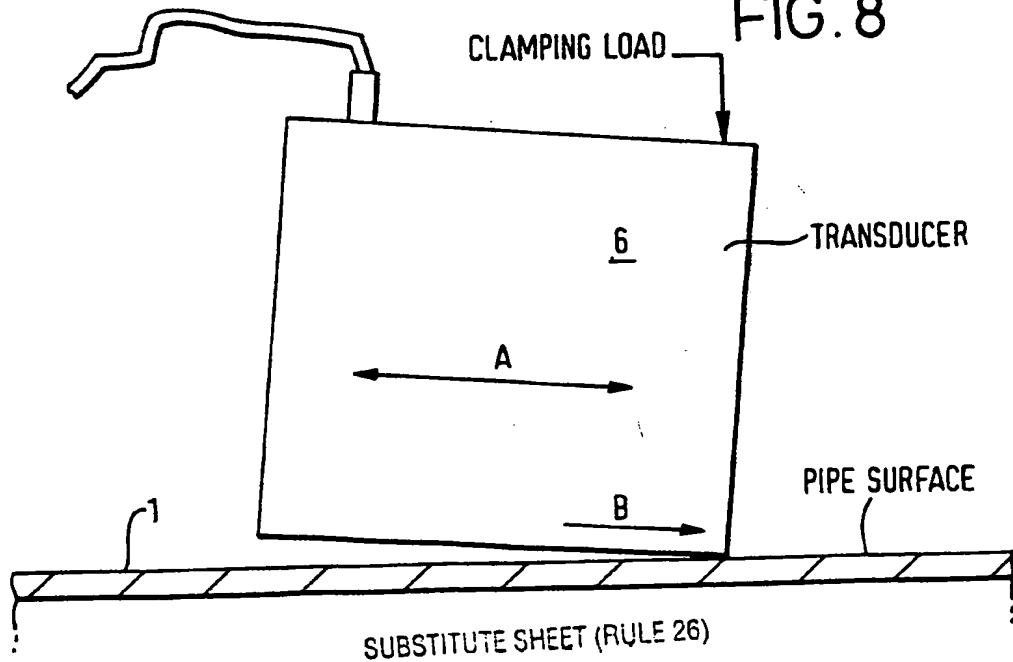


FIG. 8



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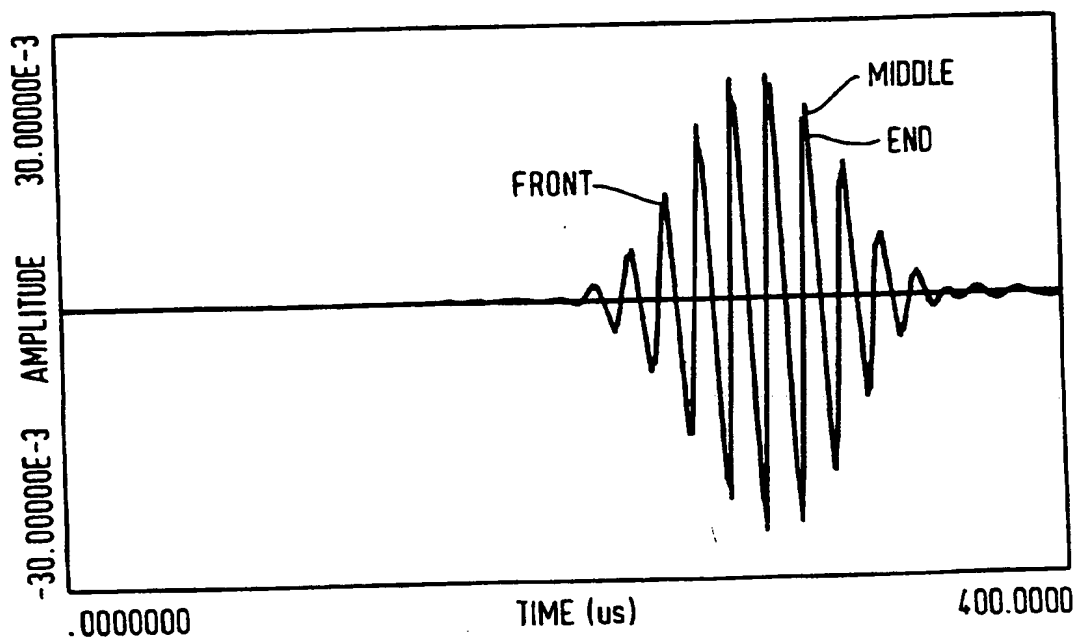
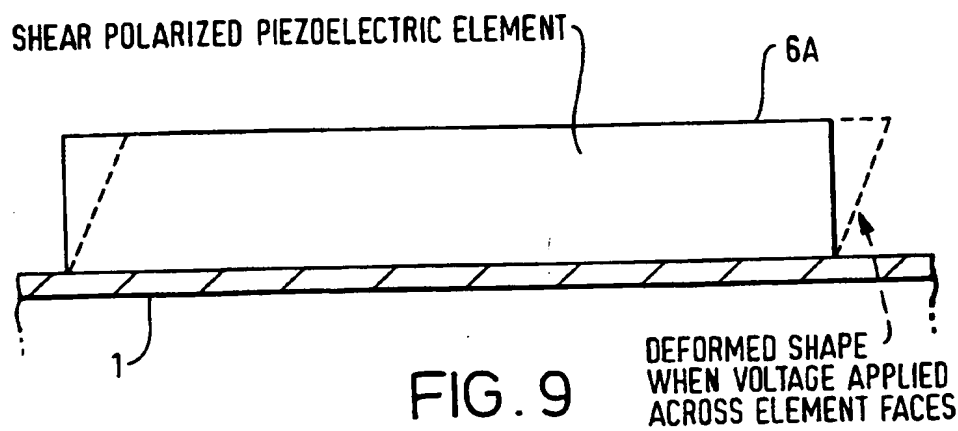
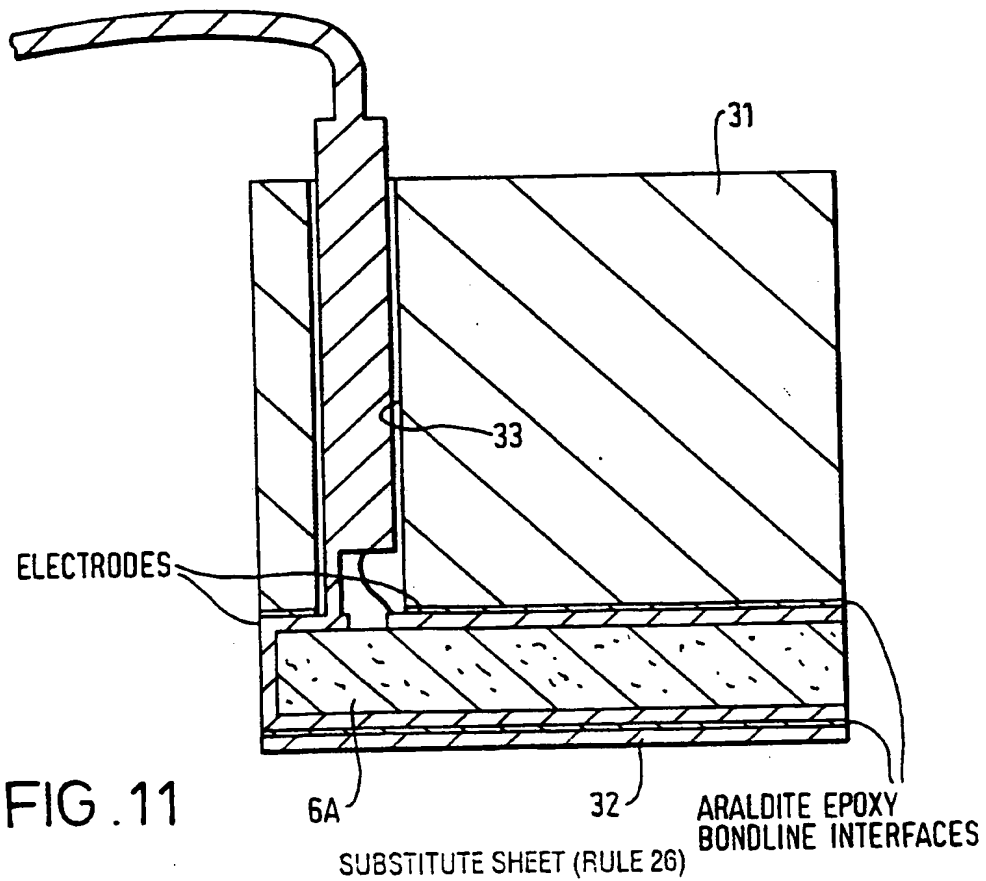
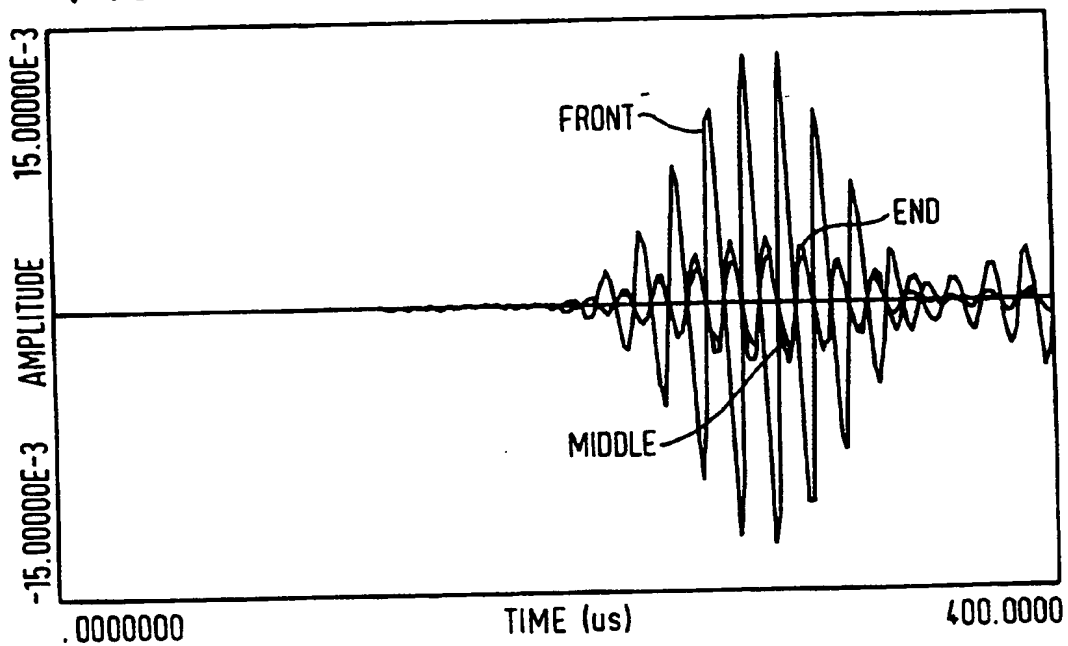


FIG. 10a

SUBSTITUTE SHEET (RULE 26)

FIG. 10b

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 95/02482

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01N29/22 G10K11/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01N G10K B06B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X, P	WO, A, 95 05585 (ENPROTECH CORP) 23 February 1995 see the whole document ---	1-10, 15, 16
X	US, A, 4 561 306 (MARINO JEAN-CLAUDE ET AL) 31 December 1985 see the whole document ---	1-10, 15
A	US, A, 4 041 773 (HAULDERN ET AL.) 16 August 1977 see abstract; figures 1, 6-9 ---	1-10, 15, 16
A	DE, A, 24 45 869 (INOUE MASAO) 15 April 1976 see the whole document -----	1, 10

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- "a" document member of the same patent family

Date of the actual completion of the international search

15 January 1996

Date of mailing of the international search report

10.04.96

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Authorized officer

Kouzelis, D

INTERNATIONAL SEARCH REPORT

International application No.

PCT/GB95/02482

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Claims 1-10, 15, 16: apparatus for inspecting pipes
Claims 11-14: particular type of transducer

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-10, 15, 16

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 95/02482

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO-A-9505585	23-02-95	AU-B- 7526994	14-03-95
US-A-4561306	31-12-85	FR-A- 2554163	03-05-85
US-A-4041773	16-08-77	AU-B- 506655	17-01-80
		AU-B- 1845376	13-04-78
		CA-A- 1059614	31-07-79
		DE-A- 2645274	28-04-77
		FR-A,B 2327541	06-05-77
		GB-A- 1561811	05-03-80
		JP-C- 1321428	11-06-86
		JP-A- 52053490	30-04-77
		JP-B- 60045370	09-10-85
		NL-A- 7611197	13-04-77
DE-A-2445869	15-04-76	NONE	